Recalcitrant Problems in Environmental Instrumentation

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ABSTRACT

Frontiers in any science are generally defined by measurement limitations, and that is especially true in environmental biophysics. Among the more persistent issues are surface–atmosphere exchange, soil water and solute fluxes, plant water status, and plant/soil nutrient status. Measurement of surface–atmosphere exchange is particularly critical to global climate change research. Despite advances in instrumentation, accuracy of flux measurements, particularly eddy covariance, remains unacceptable, partly because the underlying assumptions of stationarity and surface homogeneity are so restrictive. Even when these assumptions are valid, the method appears to systematically underestimate for reasons that are not yet well understood. Similarly, soil water and solute fluxes cannot yet be measured accurately and routinely, hampering water quality research. Recent advances in tension lysimetry offer hope for improvement, but most field experiments still rely on modeling of water and solute flow, supported by indirect measurements of ancillary variables, e.g., soil water content, soil water potential, and solute concentration, at discrete points in time and space. A third area of ongoing concern is that of plant water status. The major uncertainty here concerns which property should be measured. Nearly all of the effort over the past 30 yr has been directed at measuring water potential, but water potential measurements are equilibrium measurements, and plants operate in dynamic environments. Furthermore, many physiological processes appear to be more related to relative water content than to water potential. Finally, more accurate and more timely (e.g., in situ) measurements of plant/soil nutrient status are sorely needed to take advantage of the promise of precision agriculture.

Advances in the understanding of our environment cannot proceed too far ahead of our ability to measure. Even the rare individual with the Einsteinian intuition to see an explanation without the benefit of data must await the development of instruments and their confirming numbers before the concept is generally accepted, which can take years or decades. For the rest of us, conceptual understanding and measurement capability are more tightly coupled. For example, our understanding of the full environmental impact of chlorofluorocarbons (CFCs) developed only after the advent of high-accuracy instruments for measuring UV radiation and stratospheric ozone concentrations. The underlying concepts regarding CFC reactions with ozone were already known, as were the UV-absorbing properties of ozone, but the extent of depletion and its unusual spatial pattern would likely not have been guessed, and a global CFC ban would certainly not have occurred, without direct field measurements. Most if not all of the issues currently in the forefront of environmental research (e.g., human impacts on water quality, efficiency of agricultural water use, and trace gas impacts on global climate change) similarly contain stubborn instrumentation problems. I have made no attempt to cover all of them, instead choosing a few that are notable either for their importance or their longevity. Coincidentally, most of the issues chosen are among the many problem areas to which Gaylon Campbell has made seminal contributions. In the arena of surface–atmosphere exchange, he was an early principal in the development of sonic anemometry and open-path hygrometry (Campbell and Unsworth, 1979; Campbell and Tanner, 1985). He and his coworkers have also made numerous contributions to the subject of soil water and solute fluxes (e.g., Riha and Campbell, 1985; Campbell, 1985, 1988; Campbell and Anderson, 1998) and to the measurement of plant water status (Campbell et al., 1973, 1979; Rawlins and Campbell, 1986). These efforts have considerably advanced our understanding, but routine, accurate determination of these and other environmental variables continues to provide an energizing challenge for those of us with a passion for measurement and instrumentation.

SURFACE–ATMOSPHERE EXCHANGE

This is the central issue of micrometeorology. Originally, water vapor transport was the primary interest, and its measurement remains important for a variety of purposes, but the transport of other scalars has assumed increasing attention in recent years. Particular emphasis has been placed on the exchange of gases such as CO_2, methane, and nitrous oxide that absorb appreciable infrared radiation, since human-induced increases in their atmospheric concentrations may alter the earth's energy balance. Indeed, there are now flux measurement networks throughout the world devoted to this effort (Baldocchi et al., 1996). Considering the attention and money that has been devoted to measuring atmospheric transport, it is surprising that it remains poorly resolved. Comparisons with energy balance measurements show mean errors in water vapor transport measurement that often exceed 20%. For other gases, there is generally no check of accuracy available, but presumably their behavior is no better.

However, the barriers to more accurate measurement of surface exchange processes may be more conceptual than instrumental. The fundamental validity of eddy covariance has always been unquestioned, in part because of its powerful theoretical simplicity, but perhaps more because there were no fast-response sensors capable of rigorously testing and applying it. Now that there are infrared gas analyzers for water vapor and CO_2, and tunable diode laser spectroscopy systems for a range of

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Abbreviations: CFC, chlorofluorocarbon.

other trace gases, a mountain of data is accumulating, and a disturbing amount of it must be discarded or at least marked as questionable. Most scientists take great pains to regularly check the accuracy of their analyzers; the suspicion is growing that instrument error is not the problem. Rather, it appears that the assumptions of eddy covariance, primarily those of stationarity and surface homogeneity, are so restrictive that they preclude the continuous measurement that is necessary for a time-integrated flux of extended duration with acceptable accuracy. At a long-term site over a Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] forest in British Columbia, careful winnowing of a 50-d data set that initially contained more than 2500 half-hourly CO_2 flux values left a residual set with approximately 600 *acceptable* numbers; more than three-fourths of the data were rejected, most for either insufficient stationarity or lack of turbulent mixing (Drewitt, 2002). Problems of this sort have a diurnal bias—nighttime measurements are afflicted more frequently than those in the daytime, potentially introducing a dangerous bias in the integration of long-term CO_2 measurements.

Also vexing is the mounting evidence that even when the underpinning assumptions are in place, there is a tendency of eddy covariance to systematically underestimate turbulent fluxes. Comparisons of latent and sensible heat flux measurements with surface energy balance often show a failure on the part of eddy covariance to close the energy balance by 20 to 30% (Twine et al., 2000). Wagner-Riddle et al. (2000) have concluded that this is so systematic that they multiply their flux data by 1.3, *even though they use the aerodynamic method rather than eddy covariance*, because the stability corrections that they use were developed using eddy covariance data as ground truth.

Why does eddy covariance come up short? There are a number of potential culprits—in fact, nearly all of the possible sources of error lead to diminution of the covariance. These include the spatial separation of the wind and concentration sensors, for which correction algorithms have been reported by Laubach and McNaughton (1999); non-zero vertical velocity of dry air at the point of measurement, presumably caused by advection or terrain irregularities, for which corrections have been proposed by Paw U et al. (2000); and missing high-frequency portions of the covariance, for which corrections have been proposed by Massman (2000). A more difficult problem may be hiding in larger-scale, low-frequency motion (Baldocchi et al., 1996). In principle, this could be accounted for by increasing the averaging period, but in practice, this may seldom be possible without violating stationarity constraints.

A more general problem with micrometeorological techniques is the assumption that the underlying surface is a uniform source or sink for the scalar of interest. We know that this is rarely the case; the burgeoning activity in precision agriculture is an implicit acknowledgment that field-scale variation in net C exchange is a widespread phenomenon, and this is in managed ecosystems where every action, from fertilizer application to tillage to single-cultivar planting, is geared toward homogeneity. The spatial variation in natural ecosystems must be generally far greater. Of course, small-scale variability, over distances of a few meters, is of little concern since it gets mixed out before it reaches the height of measurement. Larger-scale spatial variation, of the order of tens to hundreds of meters, is the problem. The direction, shape, and extent of the flux *footprint*, or the area contributing to the measured covariance, change constantly as wind direction and atmospheric stability change. When this is superimposed on underlying variability in surface exchange, it injects noise in the flux measurements, even in the absence of any sources of error, for which it is difficult to imagine an appropriate filter.

A thorough reader of micrometeorology literature over the past decade or so might draw two conclusions. The first is that in the area of flux measurements, the ratio of methods papers to application papers is exceedingly high. The second is that, despite this, more methods research is needed. These seemingly contradictory statements reflect the fact that current methodology is still inadequate to solve many of the environmental problems to which it potentially could be applied.

Soil Water and Solute Fluxes

Just as flux measurement has been at the core of micrometeorology, so has it been with soil physics. And as frustrating as turbulent flux measurement has been, the situation below ground has been even more bleak. Widespread concern about groundwater contamination has spurred extensive research efforts on the impact of land use practices on water and solute flow through soil, yet the only cases in which water and solute fluxes through soil have been directly measured have been in closed systems—either fully enclosed drainage lysimeters or tile-drained fields with impermeable lower boundaries. In almost all other field studies, fluxes have not even been measured but rather inferred from discrete measurements of soil water content or matric potential, knowledge of upper-boundary conditions, guessing of lower-boundary conditions, approximations of transport coefficients, and a numerical model. This approach can work tolerably well in a macroscopic sense to at least produce a visually acceptable match between measured and simulated water content profiles, but there is little evidence that it is a reliable estimator of flux dynamics, particularly for solutes. Of course, the primary reason for the dearth of such evidence is the lack of available flux measurement tools.

A promising recent development is the equilibrium tension lysimeter described by Brye et al. (1999). It is a stainless steel box with a porous surface that is buried in the soil and connected to a vacuum source. The vacuum is adjusted to maintain it as closely as possible to the separately measured matric potential of the surrounding soil at the same depth so that the water flux will neither converge nor diverge at the lysimeter. Periodically, the lysimeter is pumped out. The measured quantity of water and solutes yields the mean flux of each over the time period dating back to the previous emptying. Subsequently, enhancements of the method have included automated rather than manual control of suction and continuous measurement of water depth in the lysimeter, which provides better temporal resolution of water flux. Lentz and Kincaid (2003) have also described a controlled-tension lysimeter for collecting leachate. Gee et al. (2002) have described a simpler device that has no control of suction but is easier to emplace and operate. Such a device will probably work reasonably well in sandy soils, but flux divergence will likely be a problem in finer-textured soils. Consequently, simple, direct measurement of soil water and solute flow remains a challenge.

Plant Water Status

Humans have been attempting in some fashion to estimate the water status of plants ever since they discovered that yields could be improved with irrigation. The earliest reported scientific observations of plant water status were probably those of Stephen Hales (1727), whose ingenious experiments on plant water relations are described in detail by Kramer (1949). Hales made sap gauges by attaching glass tubing to the cut ends of branches and roots, from which he obtained observations sufficient to deduce a wealth of information about the flow of water in plants. Progress has been fitful since. Over the past 30 yr or so, a number of elegant tools have been developed for measuring the equilibrium thermodynamic state of water in plant tissue (Boyer, 1995), but these have not been widely used in any field diagnostic sense or as the basis for making management decisions. The natural environment in which plants operate is simply not conducive to equilibrium measurements. Insolation, temperature, atmospheric humidity, and wind speed all can affect plant water status or water potential measurements, and all are inherently unsteady.

Even if plant water potential measurements could be made accurately and routinely in the field, the value of the data is uncertain. As Sinclair and Ludlow (1985) pointed out in the eloquently titled "Who Taught Plants Thermodynamics?", many of the physiological processes that go on within plants, though water dependent, are not well correlated with water potential. Passioura (1988) elaborated on this, noting the false comfort with which plant physiologists had embraced the apparently unifying concept of water potential. As he noted, one of the principal appeals of water potential, namely that it is the driving force for water flow, does not even apply in plants, where solute effects and the properties of membranes complicate matters. What then to measure? There probably is no single answer. Physiologists studying the mechanisms of drought tolerance need different information than growers who are attempting to optimize production of an irrigated crop. Hence, if we are compiling a wish list, our request might be a broader suite of measurement tools.

One potentially valuable and seemingly viable approach might be the use of dielectric methods to measure relative water content. The permittivity of water is so large compared with other plant constituents that the apparent dielectric constant of a leaf, K_L, should be a strong function of water content. The challenge is to develop a sensor configuration capable of accurately measuring K_L without unduly affecting leaf physiology. Some preliminary research has been done by Ferre and Livingston (personal communication, 2001) using remote shorting-diode waveguides on printed circuits, and it has also been suggested that the measurement could be made in the frequency domain with a flexible etched circuit waveguide (G. Campbell, personal communication, 2001), but a working system has not yet been described in print.

Plant and Soil Nutrient Status

The mantra of precision agriculture is "providing what is needed (and presumably no more), when it's needed, and where it's needed." It sounds simple, but it implies a measurement capability that simply doesn't exist currently. Potassium and P are sufficiently stable and immobile under most conditions so that annual fertilization guided by soil testing is generally adequate, but N is another story. Nitrogen exists in a variety of forms, only two of which can be used by plants, and it is continually being transformed both organically and inorganically. Strategies to reduce nitrate contamination of groundwater by metering its application to match demand require a means to assess either the current N content of a crop or the N-providing capability of the soil to which the plant has access, and to do so rapidly and reliably at multiple points in a field. Most attempts to measure crop N status have been colorimetric, optically detecting the *greenness* of a leaf or a canopy. The measurement can be made with hand-held devices, or it can be remotely sensed. It is really a chlorophyll detection method, and indeed the hand-held instruments are usually referred to as chlorophyll meters. As a management tool, best results have been obtained when the measurement is made differentially, i.e., referencing crop greenness measurements to measurements made at the same time on a well-fertilized reference strip (e.g., Eghball and Power, 1999). The correlation between chlorophyll content and leaf N content is generally high, but by the time plant N levels have dropped enough to affect greenness, it is often past the point at which N should have been applied. Another way of looking at this is that plant-based measures have no predictive power; they cannot indicate how much N is available at each point in the field for future crop needs.

A method for measuring and forecasting total plant-available soil N across the landscape is probably not a realistic goal, in large measure due to the aforementioned complexity of the N cycle. A more modest, and possibly attainable, goal is a method for measuring and mapping soil nitrate concentrations. A preliminary system was reported by Adsett et al. (1999) that included a soil sampler, conveyor, extraction unit, and nitrate electrode, all mounted on a tractor and controlled by a microcomputer to continuously process samples at regular intervals. Individual components worked well in laboratory tests, but they encountered a variety of operational problems during field tests of the entire system. Presumably others are working on this problem, perhaps with completely different approaches, but at present there is no viable means for a rapid, agronomically useful field measurement of soil N status.

CONCLUDING REMARKS

There is a natural tendency, and it is not new,[1] to think that all of the important problems have already been solved. To the contrary, there will always be problems needing attention, and their solutions will likely require advances in measurement, a statement no less true in the environmental and agronomic sciences than it is in physics or medicine. The question of what to measure is often more difficult than the question of how to do it, emphasizing the importance of conjoining science and engineering. Therein lies the value of those rare individuals like Gaylon Campbell, who are adept in both arenas. His intellect, ingenuity, and affinity for instrumentation have fueled a remarkable career that has measurably advanced our understanding of the world around us.

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[1] "Everything that can be invented has been invented."
—Charles H. Duell, Commissioner, U.S. Office of Patents, 1899.